Optical and VLF Imaging of Lightning-Ionosphere Interactions

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LONG-TERM GOALS

This work addresses one of the key topics of space physics research recommended for the next decade in the National Research Council 1995 report "A Science Strategy for Space Physics", namely, the middle and upper atmospheres and their coupling to regions above and below, specifically dealing with the electrodynamic coupling between the troposphere, mesosphere, and the lower ionosphere, driven by thunderstorm systems. Our long term goal is to quantify the effects of lightning on the mesosphere/lower ionosphere, both on a regional and global scale.

OBJECTIVES

Objectives of the current three year effort are to address the following scientific questions: What is the extent and importance of ionospheric heating due to lightning EMP? Is the optical fine structure of sprites compatible with available theoretical models? What are the horizontal and altitude profiles of ionospheric disturbances registered as early/fast perturbations on subionospherically propagating VLF signals? Are some types of thunderstorms or lightning flashes more likely to produce these disturbances? What is the underlying physical mechanism of these events? How are they related to the optical phenomena of sprites and elves?

APPROACH

Our approach consists of the use of optical and wideband VLF measurements to document high altitude optical phenomena together with the causative lightning flashes and VLF holographic imaging of the ionospheric disturbances in the form of rapid changes in ionospheric conductivity. The measurements are conducted with VLF receiver systems deployed at nine high schools spaced ~65 km apart, ranging from Cheyenne/Wyoming to Las Vegas/New Mexico, with the students and teachers at these schools involved in the program as part of our educational outreach efforts. Optical measurements consist of telescopic imaging as well as photometric measurements using a novel photometric array (called the Fly's Eye) designed and built at Stanford. The key individuals involved are graduate student(s) that are either fully funded under this program or partly funded by an associated NSF grant, ~10% effort of an engineer, and the Principal Investigator. The students are involved in all aspects of the program, including construction of equipment and software, deployment, data acquisition and interpretation, as well as educational outreach (for example by providing lectures at the high schools). The engineer is mainly involved in construction of circuit cards for the receiver.

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14. ABSTRACT

This work addresses one of the key topics of space physics research recommended for the next decade in the National Research Council 1995 report ???A Science Strategy for Space Physics???, namely, the middle and upper atmospheres and their coupling to regions above and below, specifically dealing with the electrodynamic coupling between the troposphere, mesosphere, and the lower ionosphere, driven by thunderstorm systems. Our long term goal is to quantify the effects of lightning on the mesosphere/lower ionosphere, both on a regional and global scale.

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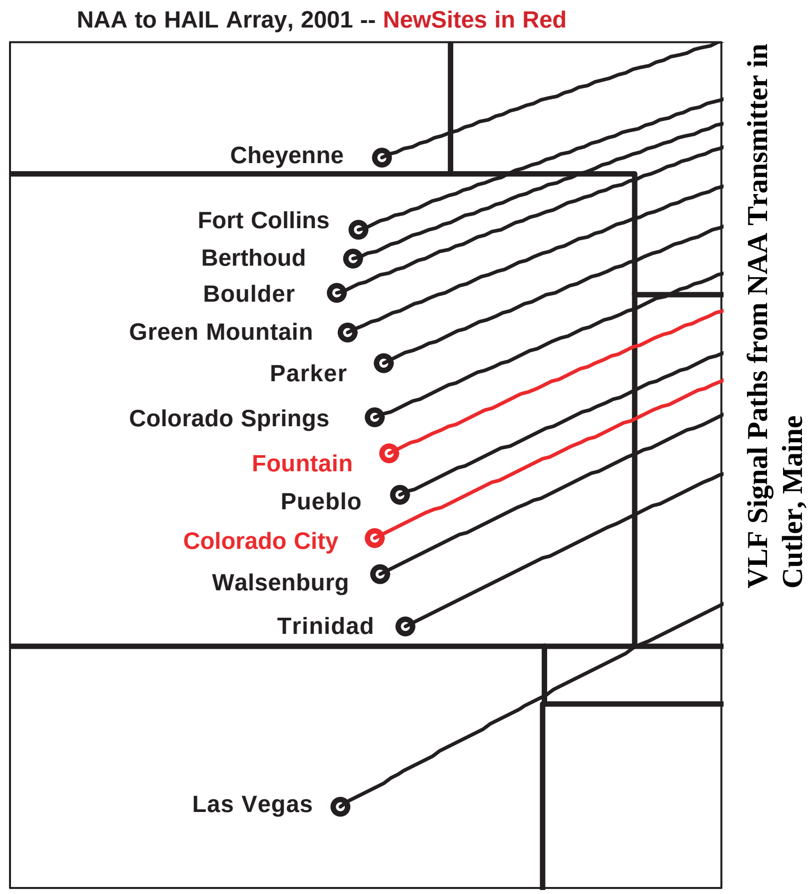
WORK COMPLETED

During the past year, holographic VLF data was acquired at the eleven Holographic Array for Ionospheric Lightning (HAIL) sites in a nearly continuous manner. In addition, two new sites have been established, at two new Colorado High Schools at Fountain and Rye High School (in Colorado City), increasing the spatial resolution of the HAIL array as shown below.



Measurements with this new system are now ongoing, and the first results will be reported at the upcoming URSI/USNC January meeting to be held in Boulder. Two scientific papers are currently under preparation for submission to IEEE Transactions for Antennas and Propagation and the Journal of Geophysical Research.

In terms of photometric measurements with the Fly's Eye instrument, work was concentrated on the completion of the papers that resulted from the Ph.D. Thesis work of Mr. Barrington-Leigh [*Barrington-Leigh et al.*, 2001a,b]. This Ph.D. work led to a number of important scientific results as itemized in the next section and is available for viewing at:

http://www-star.stanford.edu/~vlf/publications/Thesis_list.html

The telescopic imaging work carried out by graduate student Elizabeth Gerken also continued during this time. Our research during the past year involved the analysis of the data acquired during the summer months of 1998-2000 when Stanford University fielded campaigns to telescopically image sprites. The campaigns were conducted at Langmuir Laboratory (operated by New Mexico Institute of Mining and Technology) in Socorro, NM and Yucca Ridge Observatory in Fort Collins, CO. The experiment consisted of two intensified CCD cameras, two photometers, and crossed magnetic loop VLF antennas. One camera was mounted on a 16-in. diameter, 72-in. focal length Newtonian telescope with a field of view of 0.72x0.9 degrees and the other had a 50-mm lens with a field of view of 9x12 degrees. Similarly one photometer was mounted on an 8-in. diameter, 1200-mm focal length Newtonian telescope with a circular field of view of 1 degree and the second was red-filtered and had a wider field of view of 3x6 degrees. All four instruments were mounted on the same platform and were aligned. Video data was stored on VHS tapes with the photometer signals recorded on the audio channels. GPS video time-stamping and IRIG-B code were used for timing. Data from these campaigns reveal streamer structures within sprites ranging from 25 m to 200 m in width. Streamer morphologies are diverse ranging from single columns to multiply-forked structures to chains of beads. Faint downward branching is observed prior to some large sprite events. Streamers are seen to develop on time scales from less than 17 ms to over 100 ms.

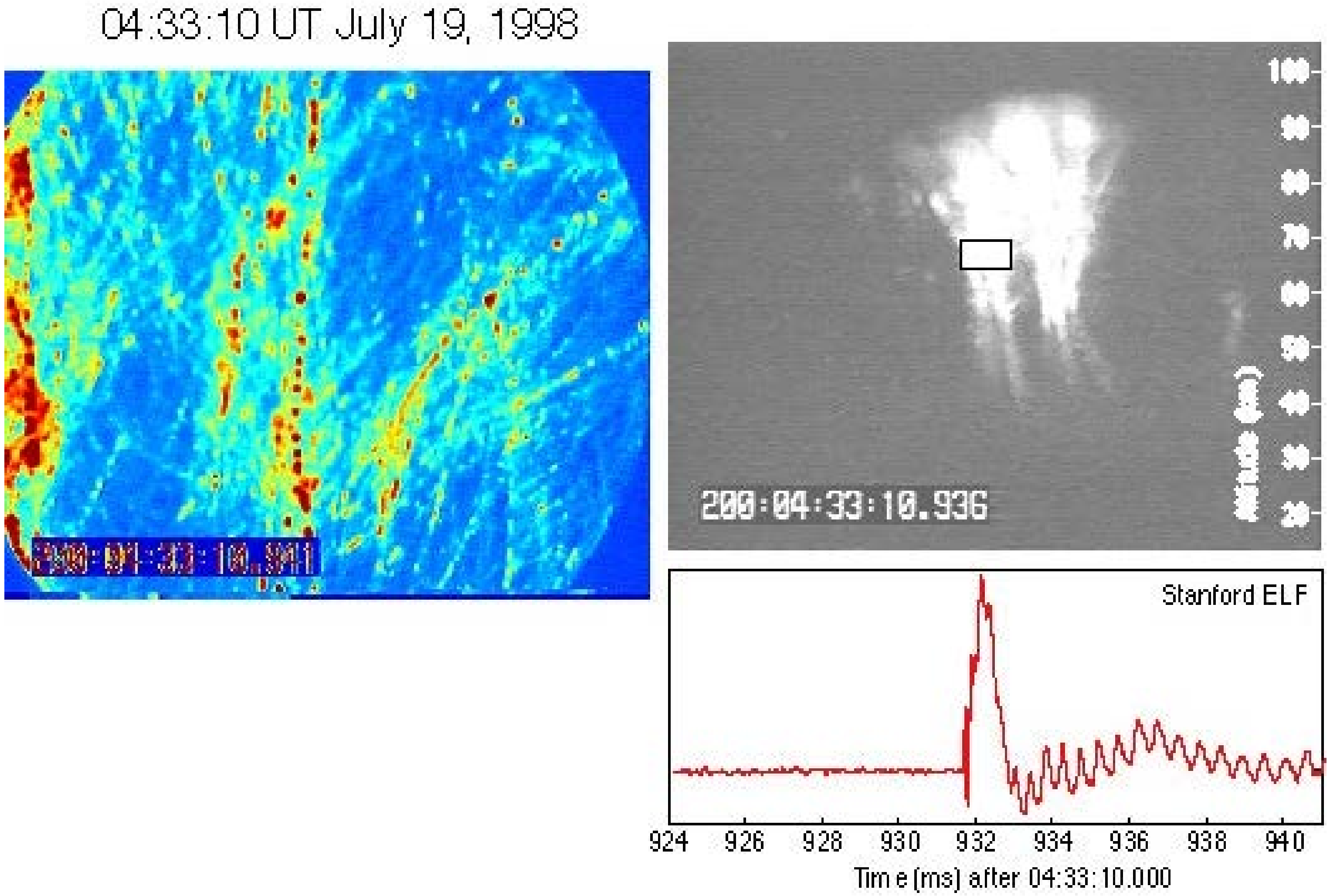


Figure 1 shows an example of beaded structure found in sprites. The upper panel displays the wide field of view camera and the lower panel show the telescopic image. A rectangle is drawn on the upper panel to show the telescope's field of view with respect to the wide field of view camera. The image is false-colored from the monochromatic video in order to better display the variation in brightness across the sprite. Below the panels is displayed the VLF recording of the radio atmospheric associated with the causative cloud to ground lightning stroke. Altitudes labeled on the wide field of view image are derived from star fields. As can be seen this is an example of fine structure found in the upper body of the sprite. It is as yet unknown what causes this beaded structure or why it occurs in some sprites and not others.

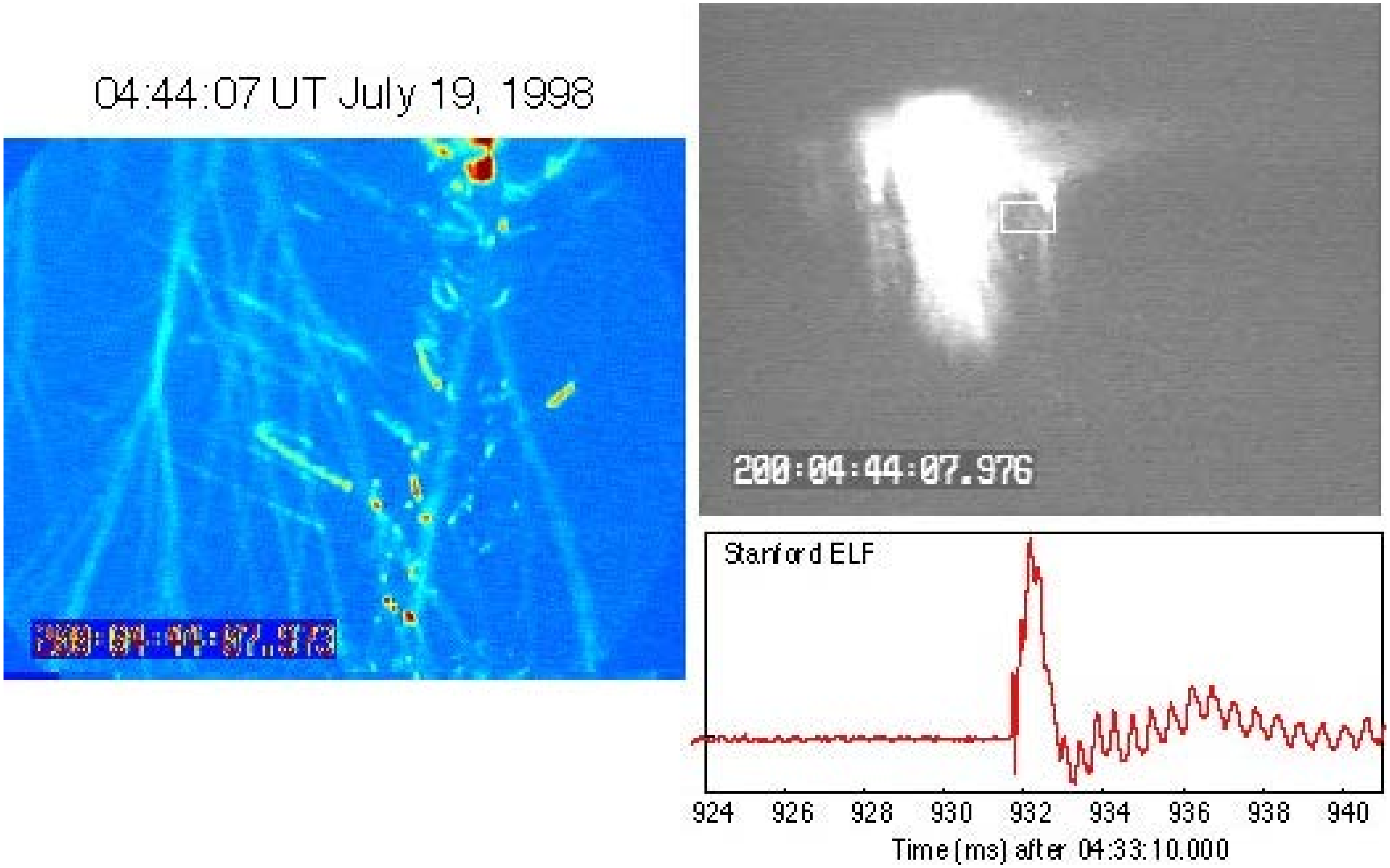


Figure 2 gives an example of a similar sprite with the telescope aimed at the lower portion of the sprite. In this case it is seen that the sprites have faint downward streamers at their base. Telescopic images of streamer structures and their direction of branching give clues to the initiation and development of the breakdown that causes sprites.

RESULTS

The following scientific results were obtained and reported in the indicated papers:

- Barrington-Leigh et al. [2001a]: The empirical extent and prevalence of the rapid optical flashes known as elves produced by lightning electromagnetic pulses (EMP), and their relationship to lightning discharges, were quantified. It was shown that elves occur in association with negative as well as positive lightning discharges. The fact that the much more common negative discharges can be just as effective in producing elves indicates that the global effect of this process on the ionosphere may be more prevalent than previously expected. A study of the spatial extent and frequency of occurrence of the heating/ionization of the lower ionosphere by lightning EMP suggests the possibility of sustained and cumulative effects on the electron density in the altitude range of ~80 to 95 km. A long standing confusion and ambiguity in video measurements carried out by various workers was resolved by demonstrating that the diffuse optical glows that are often observed on “top” of sprites are not elves produced by lightning EMP but that these compact optical forms are instead produced by quasi-electrostatic fields released by lightning discharges. These diffuse optical forms are now referred to as “sprite halos”, a term invented by C. Barrington-Leigh and accepted community wide.

- Barrington-Leigh et al. [2001b]: Measurements with the Fly’s Eye identified a quantifiable feature of the optical relaxation of bright sprites and related this to the decay of in situ electron density. This result may form the basis for a possible new method of remote sensing of mesospheric electron density changes and moreover may allow the determination of the in situ driving electric field.

- Analysis of a sequence of Early/Fast VLF events observed

- Inan et al. 2000: Analysis of a sequence of Early/Fast VLF events indicates that the so-called Sprite Halo may be the underlying cause of these events. A paper reporting this important result is currently under preparation.

- New analysis of telescopic images of sprites by Elizabeth Gerken indicates a wide range of morphologies, including upward and downward branching, beading, and streamer/diffuse glow transition regions. There is also clear evidence of faintly glowing streamer channels that appear well before the main sprite. A paper reporting these results is currently under preparation to be submitted to the Journal of Geophysical Research.

The publication of our first paper on telescopic imaging of sprites [Gerken et al., 2000] put forth the important scientific result that sprites consist of highly structured ionization channels with lateral widths of a few tens of meters or less, lending credence to theoretical models suggesting that each of the these gigantic luminous events consist of thousands of streamers

IMPACT/APPLICATIONS

The general impact of our results is the quantification of the contribution to ionospheric variability (especially the mesosphere and the D region) of lightning discharges. This contribution may be globally important, in view of the ~2000 thunderstorms active around the globe at any given time, maintaining a global lightning rate of ~100 flashes per second.

TRANSITIONS

The various Java-based and MATLAB-based analysis software developed by Stanford for the HAIL research project are being used by interested high school students at the schools that house our equipment. We are currently investigating ways of expanding this educational outreach component to other schools, which is entirely possible in view of the fact that all of the HAIL data are now available on the world wide web.

RELATED PROJECTS

The holographic VLF measurements component of our project is jointly funded by the Atmospheric Sciences Division of NSF. Other related projects include broadband VLF observations carried out at Palmer Station, Antarctica, which allows us the opportunity to observe lightning-generated whistler waves, often associated with electron precipitation events detected by the HAIL system.

PUBLICATIONS AND TALKS (after October 2000)

Cummer, S. A. and U. S. Inan, "Ionospheric E region remote sensing with ELF radio atmospherics," *Radio Science*, v. 35, p. 1437, 2000.

Barrington-Leigh, C. P. and U. S. Inan, "Identification of sprites and elves with intensified video and broadband array photometry," *J. Geophys. Res., 106*, A2, 1741-1750, 2001a.

Barrington-Leigh, C. P., V. P. Pasko, and U. S. Inan, "Exponential optical relaxation in sprites," *J. Geophys. Res.*, in press, 2001b.

Inan, U. S., R. C. Moore, and B. Decker, "Holographic Imaging of Lightning-Induced Disturbances in the Lower Ionosphere," *2000 AGU Fall Meeting, San Francisco,* California, Dec 15-19, 2000.

Inan, U. S., "EARLY/FAST Disturbances of the Lower Ionosphere," URSI *National Radio Science Meeting,* Boulder, 8-11 January 2001.

Inan, U.S., "VLF Remote Sensing of Lower Ionospheric Variability," *2001 IEEE AP-S and USNC/URSI National Radio Science Meeting, Boston,* July 8-14, 2001.

Gerken, E. A. and U. S. Inan, "Telescopic Imaging of Sprites," *Asian-Pacific Radio Science Conference*, Conference Digest, p. 135, Tokyo, Japan, August 1-4 2001.

Gerken, E. A., "Telescopic Imaging of Sprites Transient Optical Emissions Workshop," *CEDAR-SCOSTEP Meeting,* Longmont, Colorado, June 17-22 2001.

Gerken, E. A. and U. S. Inan, "Telescopic Imaging of Sprites During Summer 2000," *URSI National Radio Science Meeting*, Boulder, Colorado, January 8-11 2001.

Inan, U. S., “Lightning Interactions with Trapped Radiation,” Invited Paper presented at the *Global Environmental Modeling (GEM) Conference,* Snowmass, Colorado, June 16-22, 2001.